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Energy storage systems for renewable energy power sector integration and mitigation of intermittency

Mohammed Yekini Suberu [a,*], Mohd Wazir Mustafa [a], Nouruddeen Bashir [b]

[a] *Department of Electrical Power Engineering, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor Bahru, Malaysia*
[b] *Institute of High Voltage and High Current, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor Malaysia*

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ABSTRACT

Currently, the electric power sector is looking forward towards increasing the bent for availability, reliability and security of energy supply to consumers. This pursuit has vehemently increased the intention for integrating renewable energy (RE) into the electricity sector as a strategy to curb the problem of energy deficiency especially in isolated off-grid settlements. However, the variability in the sources of RE supply coupled with conditional changes in the level of energy consumption with respect to time has brought to focus the necessity for energy storage systems (ESSs). Despite the stochastic nature of RE produced from solar and wind energy and to some extent hydro, interest in their exploitation is still growing high due to their sustainability regarding environmental receptiveness. Thus, this paper extensively reviews the state of the art of three different kinds of energy storage technologies (pumped hydroelectricity storage, batteries and fuel cells) suitable for the integration and management of intermittency in RE. Within the context of the review, advantages and disadvantages of the various technologies are also presented. Additionally, it also pin-points on the different areas of applications of ESSs for RE integration and offers review summary on factors to be considered for selecting appropriate energy storage technology for either commercial or domestic applications. Finally, the paper concluded that ESSs selection is based on performance characteristics and fuel source used whereas no single ESS can meet all the possible requirements to be called a supreme ESS.

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* Corresponding author. Tel.: +2348036363090; fax: +60 75578150.
E-mail address: engryek88@yahoo.com (M. Yekini Suberu).

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1. Introduction

Generally, the importance of energy storage systems (ESSs) is to increase in future as more attention is concentrated on renewable energy development. High interest in RE exploitation is due to accelerated depletion of energy resources from fossil background. In traditional electrical power generation, energy produced has to be consumed immediately otherwise it will be wasted and result into economic failure. Moreover, intermittent RE such as wind and solar, though little of hydro which can be affected by fluctuations in the intensity of rainfall, cannot be stockpiled in the absence of energy storage systems (ESSs) and must also be used when available or else they will lose energy potentials as well [1]. To overcome this problem there is an inescapable need for electrical energy storage systems (EESSs) which are to be charged at a time of less energy demand and discharged during the period of high demand from customers. Therefore, EESSs refers to a method of transforming electrical energy from electrical power network into a form that can be stored for converting back to electrical energy when needed [2–4] to serve any intended purpose. Harvesting electrical energy using modern technologies to foster development is a very essential and challenging undertaking to power engineers especially to the experts in energy conversions.

Though renewable energy sources (RES) are inexhaustible in quantity but they are characterized with fluctuating power output as commonly observed in wind, tidal wave and solar power systems. Fig. 1 shows a grid electricity demand for summer and winter day as superimposed with total wind power generation for the summer day. The wind power generation system exhibits a significant and drastic variation in output power which is fundamentally not connected to the demand for electrical power [5]. This exhibits the fact that wind power output can change randomly with respect to the degree of availability of sustainable wind source. In recent past, ESSs have become a progressive area of study attracting more keen interest for RE intermittency mitigation and management of RE integration. Apart from intermittency function of energy storage systems (ESSs), conventional electricity industry also needs ESSs [6–10] to accomplish some important power systems functions. RE intermittency have some effects on the energy delivery systems especially when there are changes in load demand. This variation can produce some power quality problems such as voltage transients. One of the ways out being anticipated to improve the reliability and performance is to incorporate energy storage devices into the power system networks [11]. Exception to this basic disadvantage of RE is geothermal and to some extent biomass power which has high tendency to conveniently replace fossil energy grid systems where it is available. This intermittent effect has been one of the major factors responsible for the low competitive nature of RE technologies compare to conventional energy conversion systems for electricity [12].

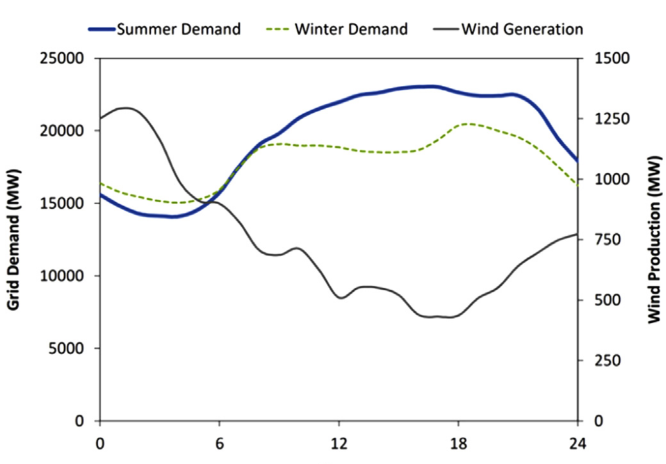

Fig. 1. Ontario grid demand for a summer and winter day overlaid with total wind generation for the summer day [5].

Energy storage systems allow for meeting customers' load demand services for extended period of time even when small renewable power generation system is used. Currently, there exist accelerated global efforts towards RE development resulting from interest in a portfolio for sustainable energy supply and ensure healthy environmental integrity. The total contribution from RE is also expected to increase in the nearest future due to continuous rise in demand for energy and emerging policies. Many energy experts have indeed argued in favor of the development of autonomous RE systems as a reasonable option to grid extension especially in remote and isolated communities. RE option can be used as a strategy to reduce dependency on fossil fuels consumption, not only for large-scale energy but also for small-scale autonomous energy systems [12,13]. The uses of autonomous RE systems have become unavoidable judging from economic constraints of fossil fuels centralized power systems. Changeability in the price of oil, fast depleting nature of crude oil resources and regional political alterations especially in oil rich countries had greatly maneuvered the availability and the sustainability of oil for energy consumption.

Many contemporary studies on RE revealed that the development of RE in off-grid approach has a potential impact on lower high cost of grid expansion and energy deficiency scenarios prevailing in developing countries. In this kind of situations, new challenges on how to stabilize and store energy output to be consumed when needed other than the time they are being generated validates the quest for the development of technologies for ESSs. Economically workable ESSs are required for energy conversion and storage which can also be converted back to electricity when needed for any application [6]. In power systems, ESSs have some important applications in operations like grid stabilization, stable power quality and reliability management, load shifting and grid operational support [1]. The reality of these functions had encouraged the

government of many industrialized countries like EU [4,6,10], United States [14–19] and Japan [6] to demonstrate their enthusiastic interest for the development and applications of electrical energy storage (EES) systems through nationally supported programmes.

In light of the above, the subsequent sections of this paper are organized as follows: Section 2 discusses three various energy storage devices as applicable to RE development. Also, within the section, the characteristic features, advantages, disadvantages and some possible areas of application of the storage systems are highlighted. Section 3 outlines some factors affecting the choice of selecting energy storage devices for electrical energy network integration. Imperatives in the power sector applications of ESSs are provided in Section 4. Section 5 gives some discussions based on the comparative analysis of the storage systems investigated in this framework which is then followed by conclusions in Section 6.

2. Energy storage systems

The history of energy storage system began in the early 20th century with the emergence of a variety of systems with the capability to store electrical energy in the form of charges and allowed to be discharged when the energy is needed. This was first achieved by the application of lead–acid accumulator which was used to supply residual loads on a direct current electricity network [3,6,7]. As the technologies continue to grow, more and more ESSs emerged such as pumped hydro system (PHS), portable and economically viable batteries, compressed air energy storage (CAES), fuel cell (FC), super-capacitors, flywheel, superconducting magnetic energy storage (SMES) and thermal energy storage devices. Fundamentally, the different kinds of energy storage devices available are classified in four main categories: mechanical (e.g. flywheel, CAES and pumped hydroelectricity storage), electrical (e.g. capacitors, SMES and super-capacitors), thermal (e.g. low and high temperature energy storage systems) and chemical energy (e.g. electrochemical, thermo-chemical and chemical storage devices) technologies.

On a broader perspective, ESSs have varieties of sub-classifications which are in essence based on types and functions. The systems are basically used for electrical energy use by charging and discharging phenomenon. However, demand for electricity in most off-grid communities varies with time just like that of urban areas with typical load profile exhibiting variations with time. Therefore, storage systems can resolve this effect on the output side of RE power network in order to make it stable similar to the conventional energy systems [20] and, in addition offer a means to segregate generation of electricity from its use [1,21]. An ESS can offer dependability to renewable resources [22,23] because intermittent sources of energy have multiple effects on the operational security, stability, reliability and efficiency of power systems [24,25].

2.1. Pumped hydroelectricity storage

Pumped hydroelectricity energy storage system was the first generation of energy storage system constructed. A diagram of PHES as shown in Fig. 2 is a system of pumping water from a lower to upper reservoir which can be scheduled on a specific cycle of time or planned based on the reduction of water in the upper reservoir. The storage capacity of PHES depends on the difference in the gravitational height between the upper and lower reservoirs coupled with the capacity by volume of reservoir and water to be pumped. Presently, PHES is the largest, most efficient and commercially sustainable ESS available in the world. Conversion efficiency of 65–85% could be achieved using PHES [26]. In many countries, economic viability as well as sustainability of this technology has been proven. In recent past, PHES has offered another development incident whereby it allows for wind power integration forming a hybrid energy storage system known wind-hydro pumped storage (WHPSS) as illustrated in Fig. 3.

There are vast numbers of literature on WHPSS focusing on case studies [28–30], as well as different background knowledge regarding optimization, modeling and techno-economic analysis [31–40]. This kind power system integration approach can be used to balance the demand and supply of electricity in an area where wind and hydroelectric power sources are potentially viable. The benefit of this kind of power system configuration is that electricity is produced and stored to supply high peak demand [28]. In the period of low electric power demand from the customers, the excess electric power generated by the wind power system can be utilized to pump water from the lower reservoir into the upper reservoir to influence high output power generation to satisfy customers' peak demand. Despite the growing nature of this technology, PHES have some draw backs which include the followings:

- Large capital investment.
- Constraint in the choice of suitable site.
- The operation of the system set-up consumes part of the energy generated.
- There is a need for careful planning and scheduling to ensure that water is pumped during low peak demand and used for the satisfaction of customers peak demand.

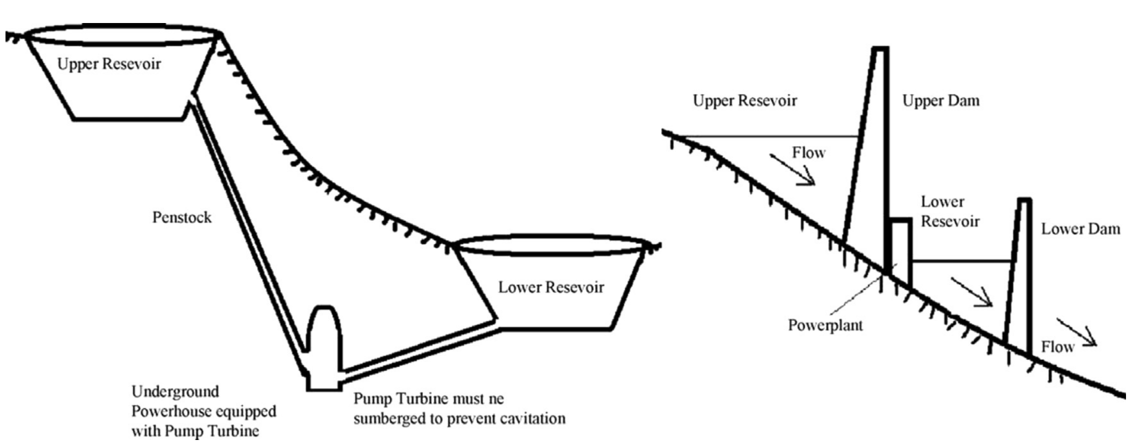

Fig. 2. Pure PHES on left and pump-back PHES on right [27].

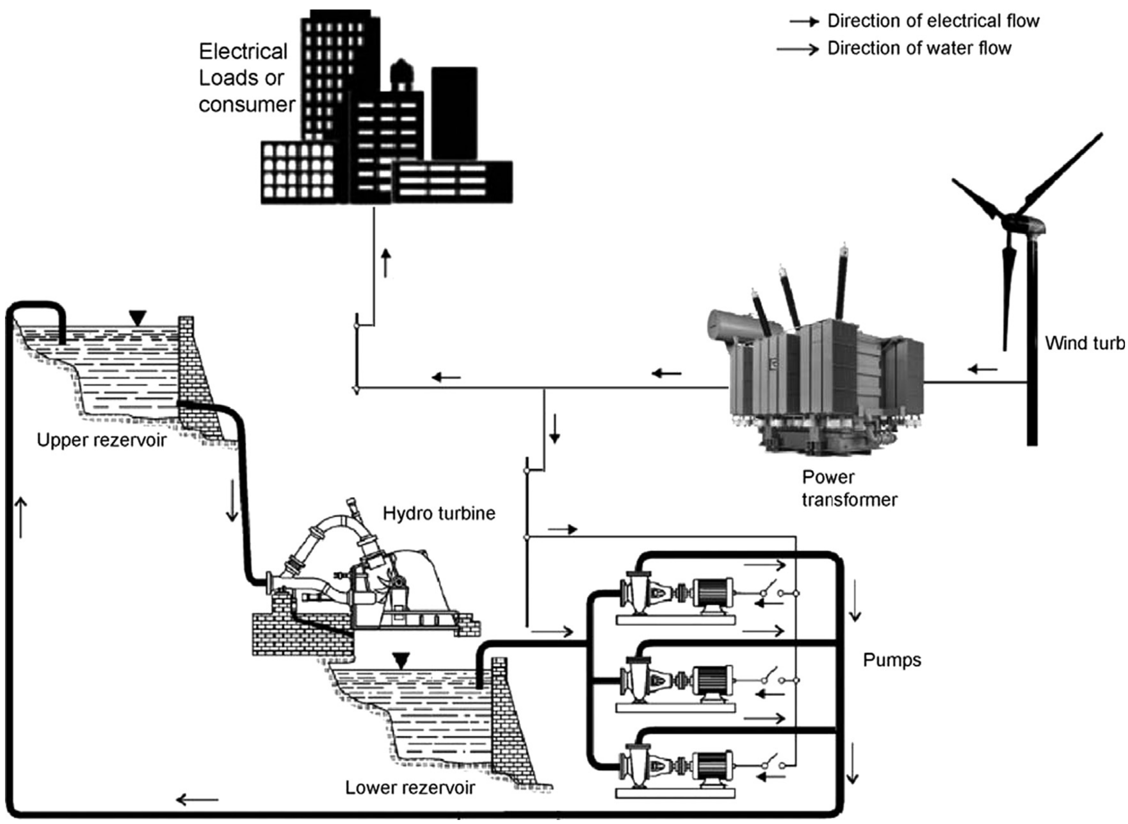

Fig. 3. Model of wind-hydro pump storage systems [28].

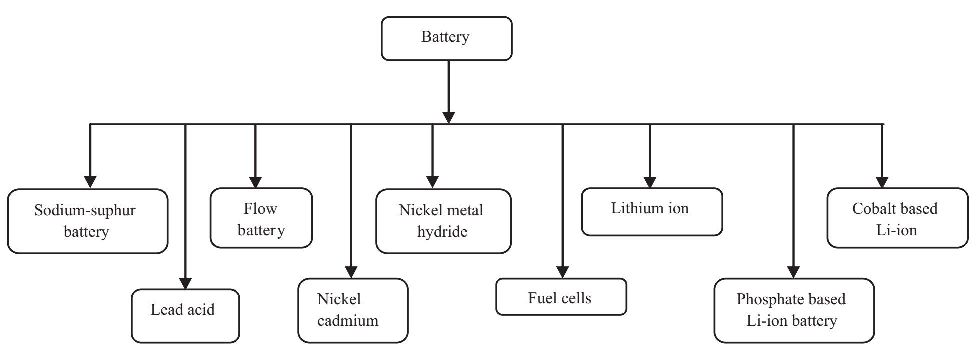

Fig. 4. Different kinds of batteries.

2.2. Batteries

Battery energy storage system (BESS) is basically in the category of electrochemical energy device as shown in Fig. 4. A BESS is an energy storage device designed to convert its stored chemical energy into electrical energy and also operates in the reverse mechanism during the charging process. Batteries have been used in a number of different applications across the world as summarized in Table 1. The basic components of BESS are batteries, control and power conditioning system (C-PCS) while the remaining part of the plant comprises protection system [41] as illustrated in Fig. 5. Depending on the power capacity, some batteries are used for high voltage applications while others for low voltage. Battery system technology is the most widespread storage device for power system applications [11,42,43]. Other targeted areas of application of battery systems are hybrid electric vehicles (HEV), marine and sub-marine missions, aerospace operations, portable electronic systems, wireless network systems and electrical grid network stabilization. Varieties of batteries used for different applications are available presently in the market. The most commonly used battery in power system applications is the deep cycle type [44] with an efficiency of nearly 70–80% [11].

Basically, batteries can be classified into low temperature internal storage and high temperature external storage systems. The low temperature versions are usually operated at room temperature. Generally, the physical design of electrochemical systems can either be internal or external storage operation. The major difference in this respect is that external storage systems allow for segregation of energy conversion section from that of active materials stored in the system. This arrangement allows for design and sizing of power and storage section. Examples of low temperature batteries with internal storage system are lead acid (PbO_2), nickel cadmium (NiCd), lithium ion and nickel metal hydride (NiMH). The high temperature versions of the external storage facility are sodium sulfur (NaS), sodium nickel chloride (NaNiCl) and flow batteries. In the external storage battery systems, the electrical conversion unit and the

Table 1
Battery technologies – characteristics and commercial units used in electric utilities [45–47].

Battery type	Largest capacity (commercial unit)	Location and application	Comments
Lead acid (flooded type)	10 MW/40 MWh	California-Chino Load Leveling	$\eta=$ 72–78%, cost[d] 50–150, life span 1000–2000 cycles at 70% depth of discharge, operating temperature −5 to 40 °C[a], 25 Wh/kg, self-discharge 2–5%/month, frequent maintenance to replace water lost in operation, heavy
Lead acid (valve regulated)	300 kW/580 KWh	Turn key system[b] Load Leveling	$\eta=$ 72–78%, cost[d] 50–150, life span 200–300 cycles at 80% depth of discharge, operating temperature −5 to 40 °C[a], 30–50 Wh/kg, self-discharge 2–5%/month, less robust, negligible maintenance, more mobile, safe (compared to flooded type)
Nickel cadmium (NiCd)	27 MW/6.75 MWh[c]	GVEA Alaska Control power supply Var compensation	$\eta=$ 72–78%, cost[d] 200–600, life span 3000 cycles at 100% depth of discharge, operating temperature −40 to 50 °C, 45–80 Wh/kg, self-discharge 5–20%/month, high discharge rate, negligible maintenance, NiCd cells are poisonous and heavy
Sodium sulfur (NaS)	9.6 MW/64 MWh	Tokyo Japan Load Leveling	$\eta=$ 89% (at 325 °C), life span 2500 cycles at 100% depth of discharge, operating temperature 325 °C, 100 Wh/kg, no self-discharge, due to high operating temperature it has to be heated in standby mode and this reduces its overall efficiency have pulse power capability of over six times their rating for 30 s
Lithium ion			$\eta \approx$ 100%, cost[d] 700–1000, life span 3000 cycle at 80% depth of discharge, operating temperature −30 to 60 °C, 90–190 Wh/kg, self-discharge 1%/month, high cost due to special packaging and internal over charge protection
Vanadium redox (VRB)	1.5 MW/1.5 MWh	Japan Voltage sag Peak load Shaving	$\eta=$ 85%, cost[d] 360–1000, Life span 10,000 cycles at 75% depth of discharge, operating temperature 0–40 °C, 30–50 Wh/kg, negligible self-discharge
Zinc bromine	1 MW/4 MWh	Kyushu EPC	$\eta=$ 75%, cost[d] 360–1000, operating temperature 0–40 °C, 70 Wh/kg, negligible self-discharge, low power, bulky, hazardous components
Metal air			$\eta=$ 50%, cost[d] 50–200, life span few 100 cycles, operating temperature −20 to 50 °C, 450–650 Wh/kg, negligible self-discharge, recharging is very difficult and inefficient, compact
Regenerative fuel cell (PSB)	15 MW/120 MWh (under development)	Innogy's Little Barford station UK	$\eta=$75%, cost[d] 360–1000, operating temperature 0–40 °C, negligible self-discharge

[a] Operating at higher temperature will reduce the life and operating at lower temperature will reduce the efficiency.
[b] At Milwauke, WI.
[c] Provides 10 MVar even when the battery is not discharging.
[d] Capital cost in Euro/kWh.

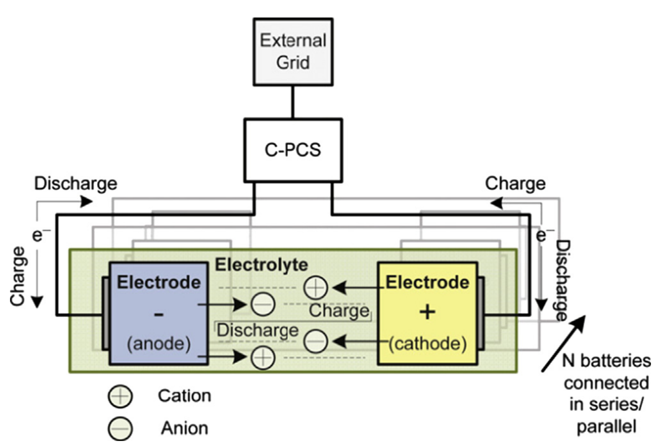

Fig. 5. Basic components and operation principle of battery energy storage system [41].

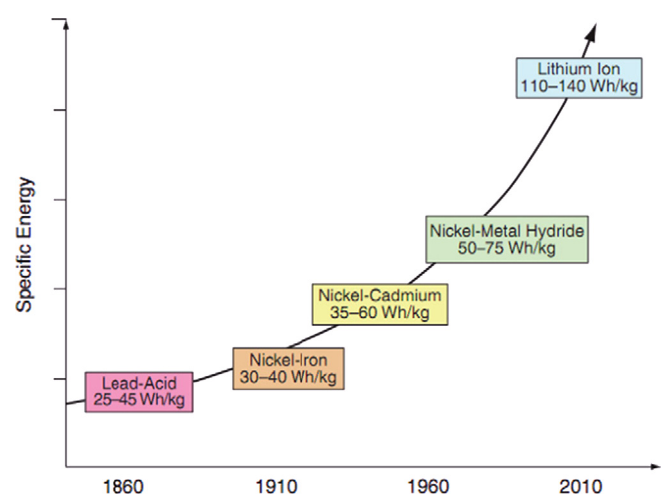

Fig. 6. Energy density increase of different kinds of batteries [54,55].

chemical storage system are actually separated but linked together for exchanging electrochemical reactions during charging or discharging process e.g. redox-flow, primary batteries with external regeneration and electrolyzer.

2.2.1. Lithium ion

Lithium-ion (Li-ion) batteries have outstanding applications in both low and high power devices as well as portable electronics and telecommunication gadgets. Their preferential usages rely on their higher energy density and higher efficiency [48]. Fig. 6 shows the energy density of various kinds of batteries with lithium ion occupying the highest rank. The anode of this battery is made up of carbon graphite while the cathode consists of lithiated metallic oxide [49,50]. The storage medium contains a mixture of lithium salts ($LiBF_4$, $LiClO_4$ or $LiPF_6$) and organic carbonates (dimethyl carbonate or diethyl carbonate). In discharging process Li^+ ion migrates from negative electrode while carrying current to the positive side with the reverse condition occurring during charging with the following electro-chemistry.

Positive electrode half-chemistry:

$$LiCoO_2 \rightleftarrows Li_{1-x}CoO_2 + xLi^+ + xe^-$$

Negative electrode half-chemistry:

$$xLi^+ + xe^- + C \rightleftarrows Li_nC$$

Contemporary lithium-ion batteries have been revealed to last further than 3000 full discharge cycles [51]. Other important features of Li-ion battery are fast charge and discharge ability

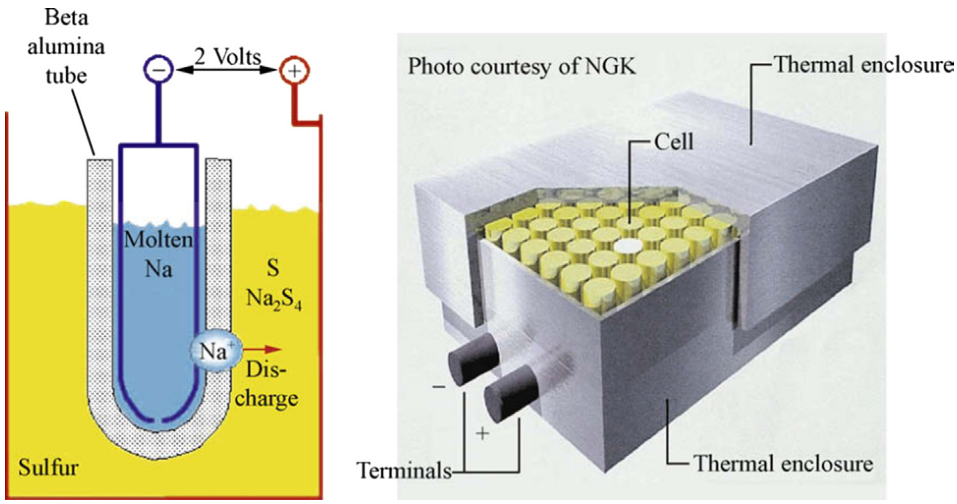

Fig. 7. Sodium sulfur battery [65,66].

[52], high energy density and specific energy of 170–300 Wh/l and 75–125 Wh/kg, respectively [53]. Also, the battery has other advantages which include the low percentage rate of self-discharge, varieties of shapes and sizes, lighter weight with high energy density, high open circuit voltage compare to NiMH, NaS, PbO_2 and NaNiCl, and intrinsically secure from environmental perspective due to the absence of free lithium metal. The major drawback of lithium ion batteries is the production cost because it depends on the lifetime, electrical performance and safety of the device. Requirement of protection circuit couples with maintenance related challenges.

2.2.2. Sodium sulfur (NaS) battery

A NaS battery (Fig. 7) is an inexpensive, high energy density, better efficiency, enhanced energy storage capacity device operating with active liquid substances. It is highly economical due to its affordable construction materials with the tendency for the materials to be recycled for re-use. This battery system is widely used in Japan and United States. It has characteristic low maintenance nature. It uses molten electrodes with sodium negative and sulfur positive. In the discharging process, sodium ions are being conducted to knock-off electron and eventually the electron generates an electric current via the molten sodium then supply external circuit to the electric load systems. A high operating temperature (270–300 °C) is required to maintain the electrochemical reaction orderliness but this temperature is supplied by the heat produced during charging and discharging cycle without any external temperature sources required for inducement. On the subject of this temperature required, some manufacturers in Japan have endeavored into a research to develop low temperature NaS. The casing arrangement of NaS is a well thermally insulated enclosure capable of maintaining the required system temperature. The electrolyte of NaS is a beta-alumina solid electrolyte simply referred to as BASE membrane. Apart from being a medium for energy carrier, the solid electrolyte is also a separator which can selectively allow only positive sodium ions to go through to produce a chemical reaction with sulfur to produce sodium polysulfides (Na_2S_4) [6].

At higher depth of discharge (DoD), NaS has a life cycle of approximately 2500 cycles. NaS has been used in many areas of power applications such as voltage regulation, peak shaving, power quality, and power output stabilization especially in wind farm, differing transmission line expansion as well as grid support system. NaS has been used to supply power during the event of grid system failure in the year 2010 in Presidio, New York. In the same country (United States) a planning is ongoing to incorporate a NaS battery into a wind power farm for demonstration purpose. Since more important areas of application of the battery are up-and-coming, therefore, it is expected that the commercial production will be possible in a nearby future especially for RE intermittency mitigation.

2.2.3. Lead acid batteries

A lead acid (LA) battery is the first kind of rechargeable battery in existence for both household and some major commercial applications. The use of lead acid battery in commercial application is somewhat limited even up to the present point in time. This is because of the availability of other highly efficient and well fabricated energy density batteries in the market. Currently, it is still predominantly being used in some sectors because of its low cost, valuable reliability, improved maturity level in the technology, extended lifespan and fast response especially in automobile systems and other applications where weight is not considered to be a threat to operational conditions. Lead acid battery is relatively cheap ($300–600/kWh), highly reliable and efficient (70–90%) [23]. LA has a useful lifespan of approximately 5 years or 250–1000 charge/discharge cycles but depends on the depth-of-discharge (DoD) [56]. There are two types of LA batteries which are valve regulated lead acid (VRLA) closed with pressure regulatory valve as the name implies and flooded lead acid (FLA). These two kinds of batteries are similar in terms of their operating principles but differ in terms of cost, maintenance strategies and physical sizes. VRLA has high purchasing cost, shorter lifespan, smaller physical size and low cost of maintenance of LA compare to FLA. The charging source of LA battery stimulates migration of electrons from the positive plate to the negative plate. In discharging state, a reverse occurrence occurs turning the electrodes into lead sulfate whereas the sulfuric acid decreases in its concentrated quality and produces lots of water. However, to manage this drawback of water production, routine maintenance is required such as replacement of distilled water as commonly associated with the flooded type of the battery.

2.2.4. Nickel cadmium batteries

In 1899, Waldemar Junger invented nickel cadmium battery (Ni–Cd). Ni–Cd which belongs to the family of rechargeable batteries has an effectively high energy density, good life cycle, sustainable efficiency, good system performance at low temperature, with characteristic wide range of sizes and ratings. Nickel cadmium batteries are robust and proven substitute to lead–acid

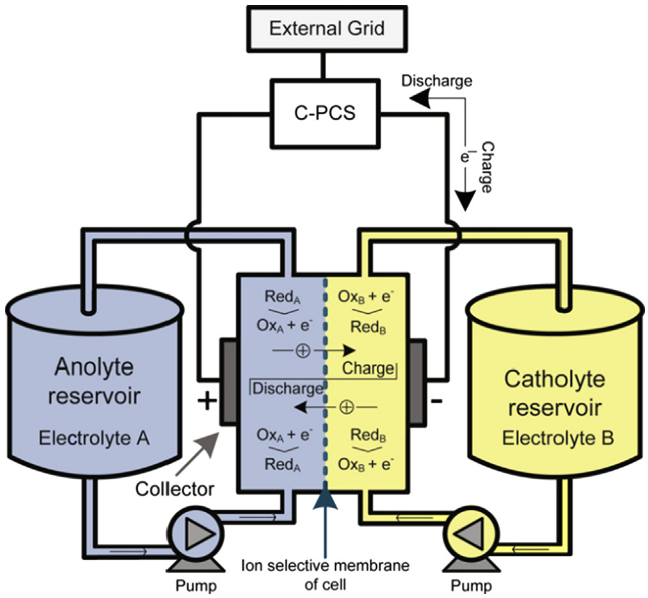

Fig. 8. Operation principle of flow battery energy storage system [41].

batteries and as well rank at the side of LA in terms of maturity [57,58]. The major components of a Ni–Cd are nickel (III) oxide–hydroxide which serves as the positive electrode and cadmium serving as the negative electrode. Potassium hydroxide which is an alkaline electrolyte is used and the content of the battery is enclosed in a well-sealed metal casing. The electrochemical reactions during charging and discharge process are the following:

Cadmium electrode reaction: $Cd+2OH^- \rightarrow Cd(OH)_2+2e^-$

Nickel electrode reaction: $2NiO(OH)+2H_2O+2e^- \rightarrow 2Ni(OH)_2+2OH^-$

The net reaction during discharge: $2NiO(OH)+Cd+2H_2O \rightarrow 2Ni(OH)_2+Cd(OH)_2$

One of the most remarkable problems associated with a Ni–Cd battery is based on their high cost due to expensive cadmium and nickel materials used in the construction. Environmental constraint is most likely encountered using the battery on the circumstance that the heavy metallic materials used are not well disposed-off. Cadmium and nickel are toxic heavy metals with high impact of health risk in humans [59,60]. Another major shortcoming of the battery is what is known as 'memory effect'. The battery needs to be fully charged and completely discharged because if the battery is moderately discharge and subjected to another charging cycle, it will forget the new charging state and remember to discharge based on its previous charging condition. This situation is not suitable because of its inherent reduction in the useful life of the battery. Another shortcoming of the battery that has been reported is self-discharge [29,51]. However, despite all the mentioned deficiencies, the battery has a good number of applications such as portable electronics, standby electric power systems, operation of aviation systems (e.g. vented type), electric vehicles (EVs) and emergency lightings due to some number of distinctive advantages among other rechargeable batteries which include the followings:

- Good quality characteristics with respect to its long cycle life (more than 3500 cycles [61]), combined with low maintenance requirements [43].
- Highly robust making it less prone to savageness with a trait of deep discharge ability for extended period of time.
- Long life span.
- Ability to withstand high discharge current.

2.2.5. Sodium nickel chloride

Sodium metal chloride batteries were primarily developed for electric vehicle (EV) use [62,63]. The development of electric vehicles (EVs) and hybrid electric vehicles (HEVs) have been increasing in the last few years [63]. The most key interest for the development of EVs and HEVs is the ESS exploitation [64,65] to increase the scenario of global energy supply level. The emergence of various kinds of batteries has compensated this important objective. Presently, infiltration of more efficient sodium-based metallic batteries has been developed with suitable characteristic to support the quest for EVs and EHVs. Sodium nickel chloride [23] battery is popularly acknowledged as ZEBRA battery with the name derived from the Zeolite Battery Research Africa Project (ZEBRA) group under the leadership of Johan Coetzer at the Council for Scientific and Industrial Research (CSIR) in South Africa. Recent development has shown that ZEBRA battery is attracting great attention as an energy storage device suitable for RE applications [62]. It is a high temperature-based (operating at an approximate temperature of 300 °C) molten salt electrolyte and high energy and power density battery. This battery has higher capability due to the high ionic conductivity of the electrolyte with approximately triple magnitude effect compared to that produced by the sulfuric acid in LA. Molten sodium serves as the negative electrode and the positive electrode utilizes nickel usually in discharge condition but nickel chloride in the charge state. ZEBRA batteries have been used in several areas of interest such as submarines, military applications, and telecommunication facilities and RE grid support.

2.2.6. Flow batteries

A flow battery also known as redox flow battery is a rechargeable battery. The operating principle of the battery is illustrated in Fig. 8. Flow battery systems are designed such that they have two external electrolyte storage reservoirs and separated from the electricity converter unit. The electricity conversion process takes place within the electrochemical cell after the electrolytes are being transported to the cell with the aid of pump. The electrolytes are electrochemically active substances flowing through an electrochemical cell with a reversible capability to convert chemical energy into electricity. Redox flow ESSs are being developed for use in off-grid village power supply and DG for electric utility services [53] which make them suitable for RE exploitation and mitigation of intermittency. They are suitable storage options for commercial energy storage. There are three prominent batteries belonging to this category: vanadium redox battery (VRB), polysulfide bromide battery (PBB) and zinc bromide battery (ZBB). Others are iron–chromium redox battery, zinc/cerium redox flow cell and vanadium–bromine redox cell. In power system engineering, flow batteries have important application with regard to generation, transmission and distribution. In generation, the batteries handle functions pertaining to generation capacity deferral, load leveling, integration with RE production, frequency control and generation dispatch. In transmission and distribution scheme, the batteries have been used for line stability, transmission facility deferral and voltage related regulations. At consumers' terminal, flow batteries play the functions to reduce consumers' peak demand, reliability monitoring, RE power quality enhancement and uninterrupted power supply. Flow batteries have potential capability to completely discharge without causing any harmful effects to the system itself. They can release energy for extended period of time. Flow batteries have potential for large

power applications but the opportunity they offered is limited by high purchasing cost as well as operating and maintenance expenditures.

2.3. Fuel cells

Fuel cells are one of the main facilitating technologies for the development of future hydrogen economy [66]. A fuel cell can be categorized as an indirect ESS. A fuel cell (FC) also belongs to the family of electrochemical energy device. The constructional feature is almost similar to that of BESS but differ in their mode of operations in the sense that the device consumes fuel (predominantly hydrogen but methanol, ethanol and other hydrocarbons have also been used) from external supply system to generate electricity. If the hydrogen is stored to ensure continuous supply, then the configuration is known as regenerative fuel cell (RFC) as illustrated in Fig. 9. By this arrangement, the system set-up behaves in a phenomenon similar linked to the operation of a battery system as the hydrogen stored can be released to produce electricity when needed. The use of fuel cell as a clean source of energy has been recognized in recent time. In a fuel cell, water, heat and electricity are produced from a prevailing electrochemical reaction between the reactants. The chemical sequence is such that the reactants flow in and reaction products flow out, while the electrolyte stays in the cell [23,28,67,68]. NASA was first to deploy and validate the commercial power applications of fuel cells (FCs) for satellite and other space undertakings. United Technology Corporation (UTC) and Francis Thomas Beacon have developed various capacities of FCs for commercial cogeneration purposes in the United States. Recent development also unveiled an attempted use of a hybrid FC/lithium-ion battery by Boeing Research & Technology Europe (BR&TE) in Spain to power aircraft which was demonstrated in 2008.

Varieties of FCs (Table 2) have been used in the last two decades for different applications, mostly for replacing internal combustions engines, providing power in stationary systems and portable power consumptions [66] as well as automobile technologies for auxiliary power supply. There are many kinds of FCs which are classified using varieties of criteria such as ions exchange mechanism and reaction types using different reactants and electrolytes. Output energy efficiency of a fuel cell is in the range of 40–65% and tends to increase provided that the process heat generated during operations can be captured for further application. Though one major drawback with regard to wider application and commercialization of FC is its associated high cost which is estimated between €500/kW and €8000/kW [69]. This cost may be reduced in future provided that

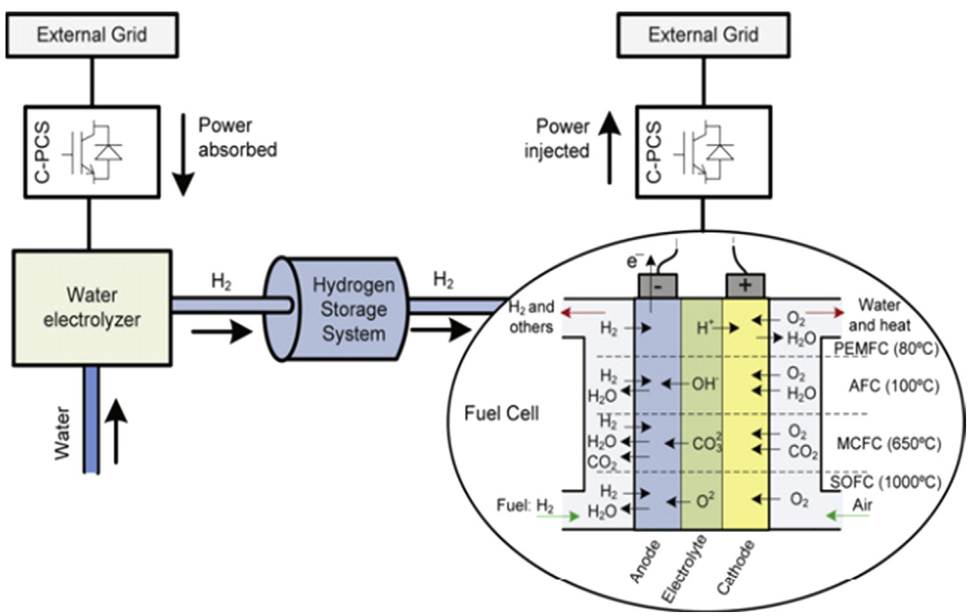

Fig. 9. Topology of regenerative fuel cell [41].

Table 2
Characteristics of different types of fuel cells [70–72].

Fuel cell type	Operating temperature (°C)	Electrolyte	Charge carrier	Catalyst anode	Fuel for the cell	Electrical efficiency (%)	Qualified power (kW)
Alkaline (AFC)	70–100	KOH (aqueous solution)	H^+	Ni	H_2	60–70	10–100
Proton exchange membrane (PEM)	50–100	Perfluor-sulfonated polymer (solid)	H^+	Pt	H_2	30–50	0.1–500
Direct methanol (DMFC)	90–120	Perfluor-sulfonated polymer (solid)	H^+	Pt	Methanol	20–30	100–1000
Direct ethanol (DEFC)	90–120	Perfluor-sulfonated polymer (solid)	H^+	Pt	Ethanol	20–30	100–1000
Phosphoric acid (PAFC)	150–220	Phosphoric acid (immobilized liquid)	H^+	Pt	H_2	40–55	5–10,000
Molten carbonate (MCFC)	650–700	Alkaline carbonate (immobilized liquid)	CO^{2-}	Ni	Reformate or CO/H_2	50–60	100–300
Solid oxide (SOFC)	800–1000	Yttria-stabilized zircon (solid)	O^{2-}	Ni	Reformate CO/H_2 or direct CH_4	50–60	0.5–100

research efforts focus on the use of economical materials for construction and growth in the technology.

2.3.1. Hydrogen fuel cell

Undisputedly, hydrogen is the most widely used fuel in FCs for electricity production. In many industrialized countries, productive efforts towards increasing the production of hydrogen from RE resources have been envisaged. Hydrogen is one of the sources of energy obtained from green fuels. This is because hydrogen with some sought-after clean qualities has been acknowledged as one of the resources which must be harnessed to support the future of energy infrastructural development. Also, new technologies with regard to hydrogen production from varieties of sources including concentrated solar energy (Fig. 10) were recorded in recent time for FC consumption. At the moment, hydrogen produced from renewable sources (biomass, wind or solar power) is currently two to three times more expensive than hydrogen from natural gas [73], thus entailing advance research and progression of efficiency optimization to contend against traditional hydrogen production processes [70]. More time is also required to move forward a hydrogen economy based on renewable sources to develop into an economically competitive commodity [70].

FCs have numerous potential areas of application for technological development such as replacement for gasoline in an automobile system (Fig. 11). Hydrogen fuel cell vehicles (HFCVs) have in recent times emerged as a zero tailpipe-emission substitute to the battery electric vehicle (EV) because of its emission free nature [75]. Hydrogen fuel cell like other traditional FC has three essential working parts which are the storage chamber for holding the hydrogen fuel, conversion units which perform the process of transforming the hydrogen fuel to electrical energy and the electrolyzer unit which helps in converting electrical energy back to hydrogen within the system enclosure. The electrochemical reaction approach for electricity production within the HFC is such that hydrogen fuel passes through the anode while the oxidant (oxygen) passes over the cathode. This cross movement allows the formation of hydrogen ions and electrons at the anode and thereby guarantees the electrons produced to flow through an external circuit for electrical energy production.

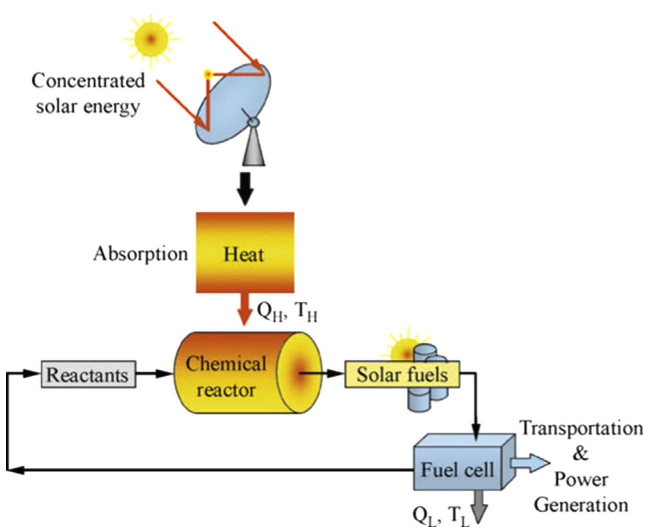

Fig. 10. Solar energy conversion into solar fuels [74].

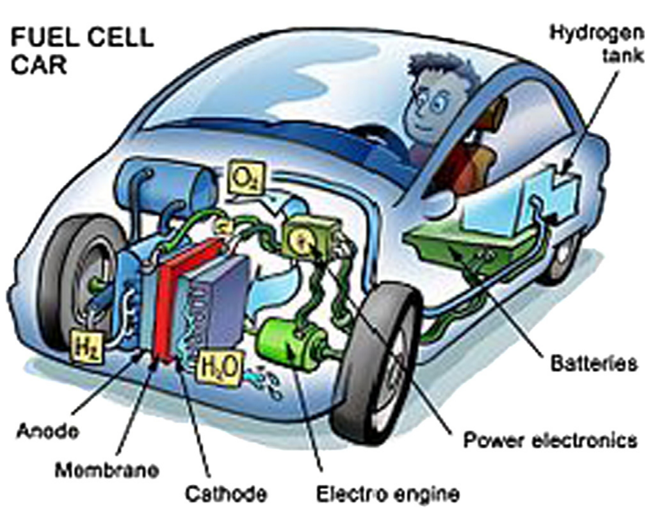

Fig. 11. Configuration of components in a fuel cell car [76].

2.3.2. Proton exchange membrane fuel cell (PEMFC)

Another type of FC with potential for hydrogen resource utilization is the proton exchange membrane fuel cell (PEMFC) (Fig. 12). PEMFC is one of the promising technologies for clean and efficient power generation in the 21st century [77]. The essential components of this version of FC are anode collector plate, anode gas channel, anode gas diffuser, anode electrode, cathode catalyst layer, cathode electrode, cathode gas diffuser and membrane. PEMFC is also known as a polymer electrolyte membrane fuel cell because unlike other FC it uses polymer electrolyte membrane and it is associated with low temperature and pressure condition. The system uses the platinum catalyst to split hydrogen molecules into protons (hydrogen ions) which must be conducted across the membrane for the proper operations of the FC. Power delivery capacity of PEMFCs ranges from 100 W to 100 KW and the operating efficiency is usually in the range of 40–50%. Advantages of PEMFC include design simplicity and robustness, low weight, high power density, ability to use atmospheric air and very low emissions. So far, PEMFCs have been used in stationary power generators [78], uninterrupted power supplies [79], portable computers [80], light weight powered vehicles [81], power bicycles [82], hybrid power buses [83] and sailing yatches [84]. Besides PEMFC, there are other hydrogen-based FC such as regenerative fuel cells (RFCs), phosphoric acid fuel cells (PAFCs) and alkaline fuel cells (AFCs). Despite the numerous advantages of hydrogen-based FCs quite some numbers of disadvantages have been observed such as high cost, sensitivity to hydrogen contamination and relatively low electrical power efficiency.

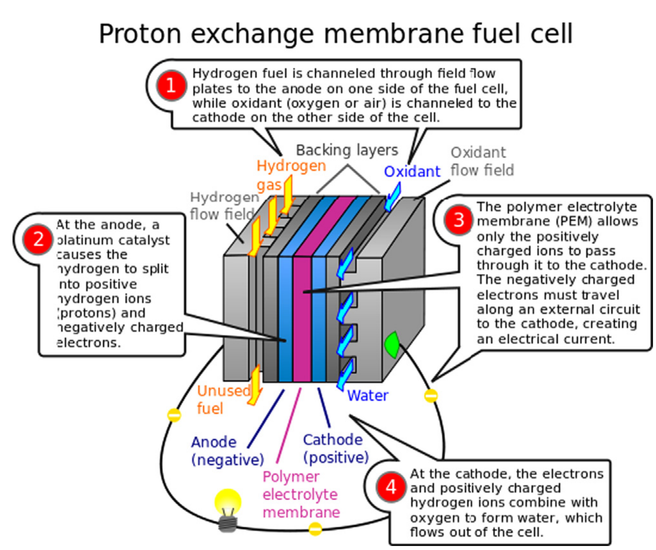

Fig. 12. A high temperature proton exchange fuel cell (PEMFC) [76].

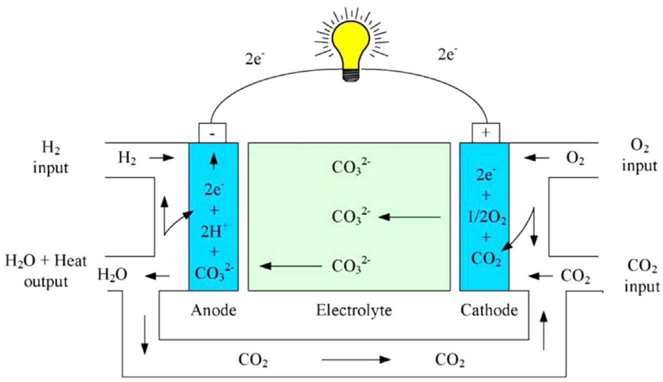

Fig. 13. Molten carbonate fuel cell principles of operation [89].

2.3.3. *Molten carbonate fuel cell*

Molten carbonate fuel cells (MCFCs) use lithium–sodium or lithium–potassium carbonate salts as the electrolyte at high temperature (roughly 650 °C). MCFCs possess high ionic conductivity compared to lithium potassium carbonate [85]. The fuel gas used in this system is a humidified mixture of H_2 and CO; the oxidant is a mixture of O_2 and CO_2 which may contain water vapor [85–87]. The operating pressure is between 1 and 10 atm. Due to high temperature required for operation, a non-precious metal (usually nickel) is used as the anode electrode while the oxide (NiO) is suitable for cathode. During operation, the high working temperature melts the salts to produce carbonate ions at the cathode electrode. The ions (CO_3^{2-}) then migrate to the anode where it combines with the hydrogen molecule to produce steam, carbon dioxide, heat and electrons. The electrons produced drift towards an externally connected circuit to generate current electricity as illustrated in Fig. 13.

MCFCs have the potential to utilize various kinds of fuels unlike other FCs. In Japan and United States, MCFCs are at present undergoing some technological modifications to handle fuels like syngas, natural gas and biogas for power generation. There is also another advantage where the platinum catalyst can be replaced with the nickel type without any documented effects. Carbonate fuel cell technology is more fuel flexible compared to other lower temperature fuel cell technologies and is well appropriate for marine, military, and traction applications [88]. The high temperature propensity of MCFC adjudges their cogeneration competence. They have also being used in many hybrid power systems. Quite a lot of MCFCs hybrid systems with fuel-to-electricity efficiencies above 70% have been conceptualized with some under development at the moment [89]. In hybrid system with turbines, MCFC can produce 55–90% electricity while the remainder capacity can be attributed to turbines [85]. On the other hand, there are also few challenges confronting MCFCs such as longer period to attain operating temperature, poor immunity to sulfur effect, and limited market penetration due to technological immaturity. In addition, the liquid electrolytes used in MCFCs have some handling difficulties.

2.3.4. *Solid oxide fuel cell*

Solid-oxide fuel cells (SOFCs) [90–93] are attractive to users of FC due to their higher efficiency for electricity generation [94,95] and are envisaged to be commercialized in the nearby future [96,97]. SOFCs use solid oxide electrolyte for conducting negative oxide ions (O^{2-}) from cathode to anode by means of either nickel or cobalt electrode operating under a very high temperature (between 700 and 1000 °C) condition. Some of the merits of this type of FCs include moderate cost, high efficiency, relatively low emissions, fast internal chemical reactions and stationary power application from few hundreds of wattage electrical powers to about 2 MW. However, there is an ongoing research towards developing a low temperature version of the SOFC with the intention to replace the oxygen ions with proton-based conducting concept called proton conducting solid oxide fuel cells (PC-SOFCs). Moreover, from cogeneration point of view, the higher temperature characteristic of SOFCs has made the system suitable for combined heat and power (CHP) applications. This high temperature state of affairs of the cell indeed eliminates the need for using expensive platinum catalyst as required in low temperature version of FCs. The most common disadvantages so far attributed to SOFCs are the problems of sulfur contamination and technological immaturity.

2.3.5. *Direct methanol fuel cell*

Direct methanol fuel cell (DMFC) is a subclass of PEMFC utilizing methanol directly as feed-in fuel for electricity production. Methanol (CH_3OH) is a renewable source of energy and is environmentally sustainable [98–102]. DMFC has lower efficiency, low operating temperature but fast becoming a reliable energy storage system due to their longer lifespan and greater energy density compare to SOFCs and lithium-ion battery. In view of these advantages, DMFCs are replacing conventional batteries in some useful applications [88]. The basic principle of operations of DMFC is the extraction of hydrogen from methanol by electro-oxidation to produce carbon dioxide at the anode without the need for any reforming. The hydrogen ions (H^+) are migrated to the cathode after crossing the proton exchange membrane and then combined with oxygen to produce water. At the cathode, oxygen is reduced to water (steam). The electrolyte used in this configuration for DMFC is quite the same as in PEMFC. The half and overall reactions of DMFC are given below:

$$\text{Anodic half-reaction: } CH_3OH + H_2O \rightarrow 6H^+ + 6e^- + CO_2$$

$$\text{Cathodic half} - \text{reaction}: \tfrac{3}{2}O_2 + 6H^+ + 6e^- \rightarrow 3H_2O$$

$$\text{Overall reaction}: \quad CH_3OH + \tfrac{3}{2}O_2 \rightarrow 2H_2O + CO_2$$

The electrical power capacity of DMFC is to some extent limited in potential but has effective operational easiness. This is because the storage and transportation means for methanol is less cumbersome compared to hydrogen which requires some level of sophisticated pressure management. DMFC is currently playing a very important role in portable power market for some mobile electronic systems such as hand-phones, digital cameras and notebook computers. Major problem of this technology are the emissions of carbon dioxide with potential to contribute to global warming if not well handled. Crossover phenomenon during the oxidation of methanol has also being reported [102]. It is a very serious problem that severely reduces cell voltage, current density and fuel utilization, and hence cell performance [103] with reduced efficiency because less than 30% of the stored chemical energy of the system can be exploited for electricity generation [104,105]. Intrinsically, heat generated from this system causes membrane electrode assembly (MEA) and water management with effects on cost, efficiency and overall power system [102].

3. Factors for selecting ESSs for RE integration

3.1. *Economic viability, efficiency and life span*

The theory of economic viability in the choice of energy storage device is highly considerable. In the circumstances of selection of an ESS, lifespan and efficiency are strategically central as they tend to influence the net capital cost of energy delivery. Capital cost of a

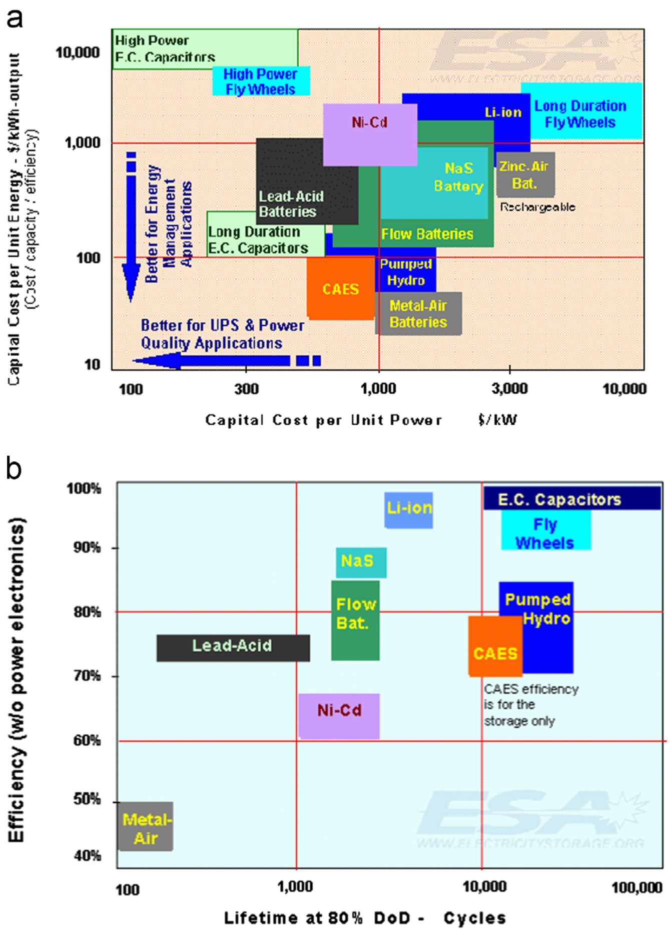

Fig. 14. (a) Storage systems as a function of investment costs per unit of power or unit of energy [108]. (b) Efficiency and lifetime at 80% DoD for each technology [108].

storage system is a very important factor; the lower the efficiency and life span of a storage system the higher it is uneconomical for use. Fig. 14(a) presents of different kind energy storage systems as a function of investment cost per unit of energy produced. Within the cycle of cost analysis for ESS, operation and maintenance cost is another integral economic aspect with the potential to contribute to the overall monetary value of the system. These two factors can determine the periodic replacement of the system but in large power application it is more reliable to use storage systems with extended life span and higher system overall efficiency. Fig. 14(b) presents the efficiency and lifetime of some prominent energy storage systems on 80% depth of discharge (DoD) for each of the system selected. Li-ion, NaS, flow battery, PHES and lead acid have appreciable efficiencies to meet both commercial and domestic demands for energy storage.

3.2. Environmental impact

Increase in anthropogenic carbon dioxide emissions into the atmosphere has mainly being attributed to increases linked with electric power generation and transportation fuel utilization [106,107] from conventional fossil energy sources. In this dimension, the need for integration of a RE portfolio for electricity generation can be credited to diminution of fossil fuel sources, exceptional increase in energy demand, global warming, local pollution and unpredictable prices of fossil fuels [108,109]. In the selection of appropriate ESS for renewable energy exploitation, environmental consideration is of prime importance. Harmful

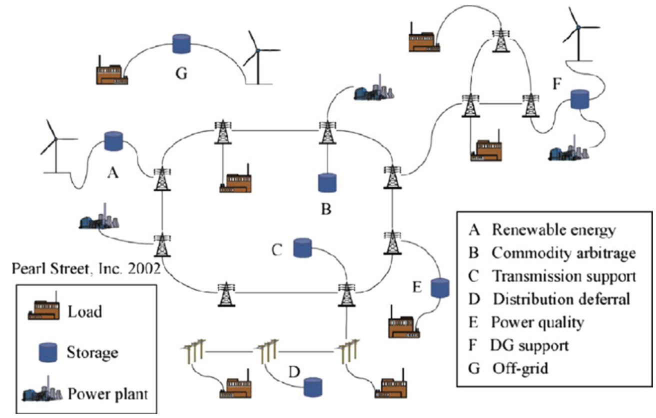

Fig. 15. Various energy storage systems' application [6].

chemical substances released from some ESSs can induce contamination of the natural quality of air, destruction of soil structure and water bodies. Pollution of any sorts can be regulated from country to country to avoid emissions of harmful substances capable of producing harmful effects on the biodiversity. At some other level, a unified global environmental restriction could be of great importance since the atmosphere is central to all. In reality, there are some degrees of variability in environmental effects caused by the three kinds of energy storage investigated in this study. PHES has a large environmental impact compared to the moderate nature of batteries and small effects from fuel cells. In the construction of PHES, a large portion of natural vegetation could be destroyed and possibly residential sites may be relocated during construction.

3.3. Integrated technical factors

On technical ground, some ESSs are more advantageous than others regarding weight per kilowatt, run time, self-discharge, storage capacity, charge time, energy density, power transmission rate, time of energy discharge, system response delay time, storage duration and operational easiness. A wide-range variation of these factors is capable of determining the selection of an ESS for any applications.

3.4. System capacity

System capacity of an ESS is synonymous to the electrical power capacity. Variability in the electrical power ranges of different kinds of ESSs have been discussed within the framework in previous sections. PHES has the highest system capacity with higher standby reserve capacity to substitute the main power generating source in a situation of unavailability or recompensate for the main power system failure.

4. Imperatives of ESSs in power sector RE integration

ESSs are used in electric power sector for diverse functions as illustrated in Fig. 15. In the figure, RE exploitation, commodity arbitrage, transmission support, distribution deferral, power quality, DG support and off-grid supply of electricity with the aid of an ESS are revealed. This illustration clearly demonstrates the multifaceted functions of ESSs in power systems.

4.1. Load management applications

RE solar photovoltaic arrays or wind turbines can provide primary energy needs. Also, an electrochemical energy storage

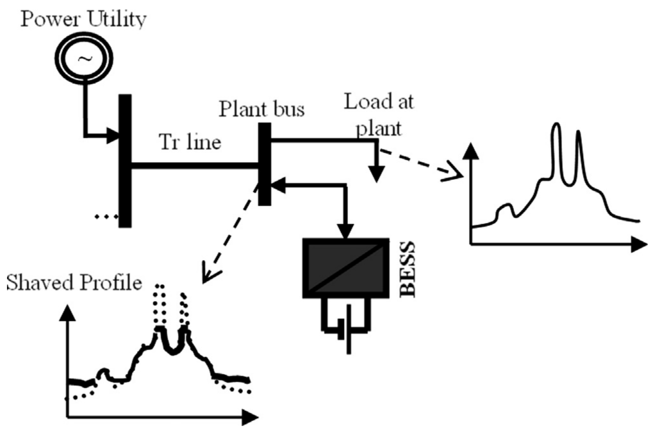

Fig. 16. Load peak shaving by battery energy storage system [115].

device can be used to store the output energy during times of surplus of power generation and distributed at the time of peak energy demand. The entire system of energy management involves equilibrium in the supply and end users energy demand service sustainability. At the point of generation, energy produced may need to be stored especially at night particularly for wind and other less energy demand periods for both solar and wind energies. However, provision can be made for the bulk of stored energy to be discharged when there are rapid changes in load demand from the customers. Consumers can dispatch energy stored in the duration of off-peak or low-cost time to manage demand on utility sourced power [110,111]. In a circumstance of high energy demand, the back-up ESSs supplement the increase load demand to prevent some technical constraints on the generation equipment while maintaining demand and supply symmetry. Another issue on energy management especially at end users terminals is peak shaving and load leveling which can as well be managed effectively using BESS as illustrated in Fig. 16. Incorporation of ESSs into a power supply system is a valuable management strategy for accomplishing charging and discharging alteration for load shaving and shifting such that the base load can be sustained over a wide range of demand time particularly in load shaving (Fig. 16). Efficient energy management systems that integrate storage facilities allow consumers to swing electricity purchases to lessen peak electric demand, thus lower electricity costs and act in response to utility quest to reduce power consumption [112,113]

4.2. Mitigation of RE of intermittency and DG support

RE sources are intermittent in nature and this behavior makes their exploitation vulnerable to fluctuations in electric power generation and their penchant for energy dispatchability. ESSs are in consequence required to mitigate this problem. The current increasing pace for RE utilization has also thrown much concern on the strategic suppression of their intermittency so that qualitative power can be delivered and reliability challenges presented by RE systems can be addressed. Looking towards this direction, the importance of RE storage applications [114,115] for ensuring grid stability in the scenario of RE grid-connected have been ascertained. Even in remote area power supply (RAPS) [114,116] the necessities of ESSs such as BESS have been observed with keen thoughtfulness. RE power systems are predominantly operated on DG basis in remote areas because of their limited electric power capacity. Load demand in such remote areas do obey the traditional load profile, and this justifies the attractiveness of ESSs to support the local DG as a means of energy planning strategy. The storage systems will reduce the need to constrain DG systems and provide a support for heavily loaded local distribution feeder.

4.3. Back-up and power quality management

Among the fundamental concern of power utility service providers is to ensure that there is continuous supply of qualitative power to the end-users' terminals to satisfy demand and maintains system protection. Renewable electricity from wind and solar energy sources has distinctive low resource supply reliability. Summarily, this conception brings the idea of renewable electricity supply security management (RESSM). Therefore, energy supply security can be defined as the ability of the electrical power system to make available electricity to end-users with a specified level of continuity and quality in a sustainable approach [117]. This challenge presents the need for backup system such as ESSs. A backup system maintains electricity supply adequacy [118,119]. One of the primary functions of ESSs is to act as back-up in power supply systems. Today, back-up generators that run on expensive fuel have been replaced with ESSs in various homes and commercial centers to supply electricity during short power outages that could last for some few hours or a day. The process of integrating back-up ESSs into a power supply network must be adequately planned such that it can compensate for power loss in an event of emergency power outage.

4.4. Improvement in the technologies of power electronics (PE)

Presently, the growing trend for RE penetration through DG and the continued uses of latest varieties of power electronic technologies for interfacing mechanism is highly noticeable. PE devices used alongside with energy storage devices are mainly used for interfacing applications. In this respect, the author in Ref. [120] stated that advanced motor drives are very much influencing the energy productions from wind power, hydropower, biogas, and energy storage systems such as flywheel energy storage. Fig. 17 shows energy storage backup system application in a fuel cell (FC) set-up for electricity using a PE network interface. The energy storage system in the network is interfaced with a bi-directional DC/DC converter. The function of the converters is to aid the transfer of power in either direction and as well improve the transient response of the system while the DC/DC inverter ensures that the reverse direction of the current and power flow is possible.

4.5. Deferment of necessities for transmission expansion

Transmission expansion sometimes becomes necessary especially when there is an increase in the demand for electricity from the supply side. In such a situation, upgrading the system becomes obligatory to avoid constraining system capacity which could lead to power system collapse. The expansion period varies from place to place but depends on the growth in demand for electricity and the financial capability to execute the project. Thus, ESSs can provide a suitable cost saving alternatives pending on when the financial resource to gratify such project becomes available. Storage devices installed across transmission lines can troubleshoot problems related to variation in demand for power on the transmission line such that the device is charged during off-peak period and discharge during high peak hours to cater for line stability and reliable power delivery.

4.6. Emerging smart-grid development

Smart energy storage system (SESS) is obviously a new level of reality in power system development. So far, impact of SESS has been felt in electric vehicles (EVs) and plug-in hybrid electric vehicle (PHEV) and the technology is expected to become more renowned with the

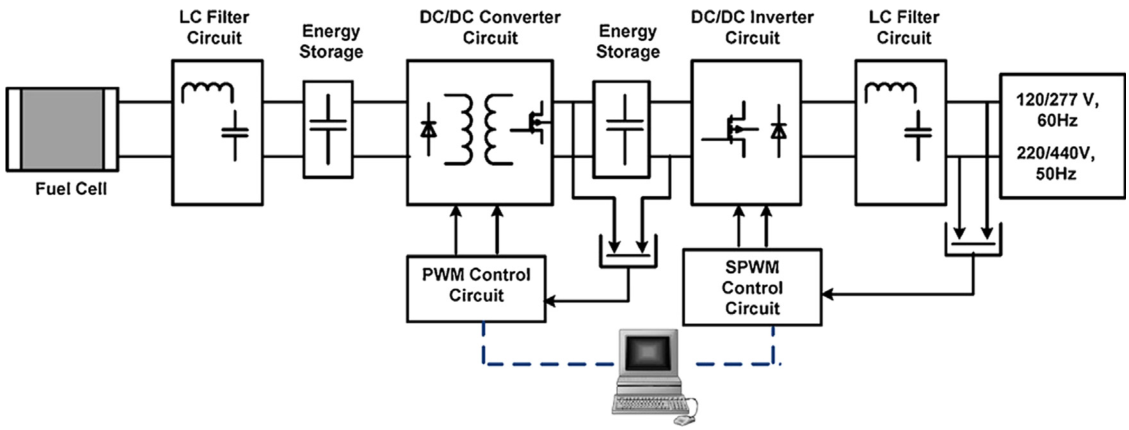

Fig. 17. Control network of a fuel cell based power system interfaced with PE devices [122].

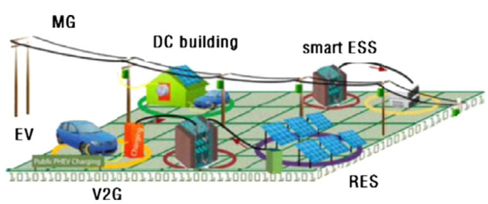

Fig. 18. MG and its future applications [124].

penetration of grid-to-vehicle (G2V) system. SESS technological development will further strengthen enormous uses of storage systems utilizing RES. This could also enhance the integration of EVs and ESS in a microgrid (MG) perception as illustrated in Fig. 18. Addition of more intelligent systems to electrical power grid requires ESSs to accomplish all their proposed functions in an effective manner. Integration of ESSs in smart-grid helps to decrease the need for expensive plants especially in events of spike-up of demand and reduces the network volatility. Therefore, governments around the world are now emphasizing on the necessity for integrating storage systems into the so-called "smart-grids" [121] of the next generation. In this foresightedness, applications of ESSs with medium and large-scale electric power capacity are envisioned potential infrastructural development in the future. Due to the sophisticated nature of smart-grid system, a reliable alternative power supply system to maintain continuity of energy supply for sustainable operation is required to maintain some advocated functionalities of the systems. ESSs attracting the most important attention in this regard are NaS and flow batteries.

5. Discussions and comparative analysis

This study basically focuses on ESSs that are primarily suitable for RE exploitations whereas high power energy storage management systems like flywheels, capacitors, super-capacitors and compressed air energy storage (CAES) mechanisms are not discussed in the framework. A large number of studies have been discussed on capacitors and super-capacitors [123–154], flywheel [6,155–157] and CAES [6,155–157]. Truly speaking, there are several integrated factors which determine the selection of storage system use for energy consumption. Cost, efficiency, energy density as well as technological maturity are very important issues as analyzed in this paper. Furthermore, technological maturity coupled with robustness is a considerable feature regarding investment in ESSs especially for commercial applications. Some of the technologies are fully matured especially with respect to battery development while others are still at developmental and experimental stages such as fuel cells. PHES is fully matured with higher commercial applicability but somewhat limited to areas where there is availability of hydro resource or where access to water can be created. There are tremendous amount of researches in the field of material technology these days for ESSs constructions to lower cost and the aspect of physical size. More technological breakthrough and barriers are to emerge as the technologies for ESSs increased.

As earlier mentioned, investment cost is another influential criterion which must be looked into when selecting an ESS for RE application. Fuel cell has the highest cost in US dollar per kilowatt ($10,000) [6] whereas it maintains the lowest efficiency among others which makes it somewhat economically challenging for both domestic and commercial applications. A capital cost of $600–2000/kW for PHES and that ranging from $300 to 4000/kW is also reported for batteries [6]. Although FC has been regarded as an indirect ESS but recent technological development in the field has brought the reversible FC into limelight. In this kind of FC, the system operation is designed such that the conventional operational procedure can be reversed. The working principle is that the reactant and electrolyte functionally produce electricity with products which can be reversed with the aid of electricity to convert the product to electricity [1]. In addition, PHES and FC have very small and negligible self-discharge phenomenon while that of batteries varies with type. NaS has the highest self-discharge rate among the family of battery ESSs with approximately 20% [158]. Generally, flow batteries have small self-discharge per day, lead acid and lithium ion fall within the range of 0.1–0.3% and nickel cadmium in the range of 0.2–0.6% per day [6]. In terms of life span in years of the various technologies, PHES has the longest life span of close to 50 years while batteries and fuel cells fall within the range of 5–15 years depending on the quality of materials used coupled with the rate of chemical deterioration of the electrolyte used.

Charge duration is also worth mentioning due to its variability from one ESS to another. The three classes of storage systems investigated here have their charging durations measured in hours but the number of hours varies with respect to each of the storage systems. Their storage duration varies as well. PHES, flow batteries and FC have their storage capability varying from hours to months but conventional batteries like NiCd, Pb–acid maintain minutes to days while NaS just seconds to hours. As regard to the energy density of the storage systems, FCs maintain some ranges between 800 and 10,000 Wh/kg, then followed by batteries in the range of 10–240 Wh/kg while PHES has the lowest of 0.5–1.5 Wh/kg [6].

6. Conclusions

In this review article, ESSs suitable for renewables applications and handling of the stochastic deficiencies in RE have been

presented. In summary, it can be said that there are a range of factors to be considered when deciding on the selection of an ESS for electricity application. The review studied so far revealed that there is no single ESS qualified to meet the entire requirements for use as an ideal ESS for either RE integration or mitigation of intermittency in the power utility sector. Some wider degree of variability in energy storage characteristics have been presented so far regarding capital cost, technological maturity, energy density, storage capacity, power capacity and areas of application. It can be said that all the three storage systems are appropriate for RE integration and intermittent power quality management. Finally, optimal combination of these factors can give the best option resting on the choice of ESSs suitable for any intended purpose in the utility industry and domestic application. In some cases, though highly dependent on the nature of the desired application and geographical location, there may be a need for electricity and storage system combination which has also been investigated by many researchers. In off-grid remote locations where RE systems like micro-hydro, isolated solar and wind energy systems are used as the main source of power supply, these storage systems can be used for intermittency management and back-up mechanism. On a grid-connected situation, PHES is the largest RE grid connected energy storage system so far while future improvement in the technologies of batteries and fuel cells is also expected to play a significant role with respect to large-scale power consumption.

References

[1] Evans A, Strezov V, Evans TJ. Assessment of utility energy storage options for increased renewable energy penetration. Renew Sustain Energy Rev 2012;16:4141–7.
[2] McLarnon FR, Cairns EJ. Energy storage. Annu Rev Energy 1989;14:241–71.
[3] Baker JN, Collinson A. Electrical energy storage at the turn of the millennium. Power Eng J 1999;6:107–12.
[4] Dti Report. Status of electrical energy storage systems. DG/DTI/00050/00/00, URN NUMBER 04/1878, UK Department of Trade and Industry; 2004, p. 1–24.
[5] Leadbetter J, Swan L. Battery storage system for residential electricity peak demand shaving. Energy Build 2012;55:685–92.
[6] Chen H, Cong TN, Yang W, Tan C, Li T, Ding Y. Progress in electrical energy storage system: a critical review. Prog Nat Sci 2009;19:291–312.
[7] Australian Greenhouse Office. Advanced electricity storage technologies programme. Australian Greenhouse Office; 2005. p. 1–35. isbn:1 921120 37 1.
[8] Walawalkar R, Apt J, Mancini R. Economics of electric energy storage for energy arbitrage and regulation. Energy Policy 2007;5:2558–68.
[9] Dobie WC. Electrical energy storage. Power Eng J 1998;12:177–81.
[10] Dti Report. Review of electrical energy storage technologies and systems and of their potential for the UK. DG/DTI/00055/00/00, URN NUMBER 04/1876, UK Department of Trade and Industry; 2004. p. 1–34.
[11] Divya KC, Ostergaard J. Battery energy storage technology for power systems—an overview. Electr Power Syst Res 2009;79:511–20.
[12] Banos R, Manzano-Agugliarob F, Montoya FG, Gil C, Alcayde A, Gomez J. Optimization methods applied to renewable and sustainable energy: a review. Renew Sustain Energy Rev 2011;15:1753–66.
[13] Zhou W, Lou C, Li Z, Lu L, Yang H. Current status of research on optimum sizing of stand-alone hybrid solar–wind power generation systems. Appl Energy 2010;87:380–9.
[14] Weinstock IB. Recent advances in the US Department of Energy's energy storage technology research and development programs for hybrid electric and electric vehicles. J Power Sourc 2002;110:471–4.
[15] Ahearne J. Storage of electric energy. Report on research and development of energy technologies. International Union of Pure and Applied Physics; 2004. p. 76–86. Available from: 〈http://www.iupap.org/wg/energy/report-a.pdf〉.
[16] Linden S. Bulk energy storage potential in the USA, current developments and future prospects. Energy 2006:3446–57.
[17] Makansi J, Abboud J. Energy storage: the missing link in the electricity value chain—an ESC White Paper. Energy Storage Council; 2002. p. 1–23.
[18] Akhil A, Swaminathan S, Sen RK. Cost analysis of energy storage systems for electric utility applications. Sandia report, SAND97-0443 UC-1350. Sandia National Laboratories; 1997. p. 1–62.
[19] Kondoh J, Ishii I, Yamaguchi H, Murata A, Otani K, Sakuta K, et al. Electrical energy storage systems for energy networks. Energy Conver Manag 2000;41:1863–74.
[20] Sørensen B. Renewable energy conversion, transmission and storage. Boston: Elsevier, Academic Press; 2007.
[21] Shively D, Gardner J, Haynes T, Ferguson J. Energy storage methods for renewable energy integration and grid support. In: IEEE energy 2030 conference, IEEE, Atlanta, GA; 2008. p. 1–6.
[22] Paatero JV, Lund PD. Effect of energy storage on variations in wind power. Wind Power 2005;8:421–41.
[23] McDowall J. Integrating energy storage with wind power in weak electricity grids. J Power Sourc 2005;162:959–64.
[24] Anagnostopoulos SJ, Papantonis DE. Study of pumped storage schemes to support high RES penetration in the electric power system of Greece. Energy 2012;45:416–23.
[25] Parsons B, Ela E, Holttinen H, Meibom P, Orths A, O'Malley M, et al. Impacts of large amounts of wind power on design and operation of power systems, results of IEA collaboration. In: Wind power 2008, Houston, TX, USA; 1–4 June 2008. [Paper NREL/CP-500-43540].
[26] Ibrahim H, Ilinca A, Perron J. Energy storage systems—characteristics and comparisons. Renew Sustain Energy Rev 2008;12:1221–50.
[27] Deane JP, O'Gallachoir BP, McKeogh EJ. Techno-economic review of existing and new pumped hydro energy storage plant. Renew Sustain Energy Rev 2010;14:1293–302.
[28] Dursun B, Alboyaci B. The contribution of wind-hydro pumped storage systems in meeting Turkey's electric energy demand. Renew Sustain Energy Rev 2010;14:1979–88.
[29] Bueno C, Carta JA. Wind powered pumped hydro storage systems, a means of increasing the penetration of renewable energy in the Canary Islands. Renew Sustain Energy Rev 2006;10:312–40.
[30] Steffen B. Prospects for pumped-hydro storage in Germany. Energy Policy 2012;45:420–9.
[31] Cristorafi C, Notton G, Poggi P, Muselli M, Heraud N, Nedelcheva S. Coupling hydro and wind electricity production by water-pumping storage. In: Environment identities and Mediterranean area. International symposium on environment identities and Mediterranean area, Corte-Ajaccio, France; 2006. p. 196–9.
[32] Guan X, Luh PB, Yen H, Rogan P. Optimization-based scheduling of hydro-thermal power systems with pumped-storage units. IEEE Trans Power Syst 1994;9:1023–31.
[33] Katsaprakakis DA, Dimitris PR, Christakis GA. Wind parks, pumped storage and diesel engines power system for the electric power production in Astypalaia. In: European wind energy conference & exhibition, Athens, Greece; 2006. p. 1–16.
[34] Bakos GC. Feasibility study of a hybrid wind/hydro power-system for low-cost electricity production. Appl Energy 2002;72:599–608.
[35] Castronuovo ED, Lopes JAP. Optimal operation and hydro storage sizing of a wind-hydro power plant. Int J Electr Power Energy Syst 2004;26:771–8.
[36] Kaldellis JK. Parametrical investigation of the wind-hydro electricity production solution for Aegean Archipelago. Energy Conver Manag 2002;43:2097–113.
[37] Kaldellis JK, Kavadias KA. Optimal wind-hydro solution for Aegean Sea islands' electricity-demand fulfilment. Appl Energy 2001;70:333–54.
[38] He W. A simulation model for evaluating Tianhuangping pumped storage hydro-plant. Renew Energy 1997;11:263–6.
[39] Sohrabi AR. Economic analysis of a pumped storage project for Iran generating system based on dynamic modeling. In: 41st international universities power engineering conference, Newcastle-Upon-Tyne, UK; 2006. p. 21–5.
[40] Hosseini SMH, Forouzbakhsh F, Fotouhi M. Determination of installation capacity in reservoir hydro-power plants considering technical, economical and reliability indices. Int J Electr Power Energy Syst 2008;30:393–402.
[41] Diaz-Gonzalez F, Sumper A, Gomis-Bellmunt O, Robles RV. A review of energy storage technologies for wind power applications. Renew Sustain Energy Rev 2012;16:2154–71.
[42] Gyuk I, Kulkarni P, Sayer JH, Boyes JD, Corey GP, Peek GH. The united states of storage. IEEE Power Energy Mag 2005;3:31–9.
[43] Joseph A, Shahidehpour M. Battery energy storage systems in electric power systems. In: IEEE power engineering society general meeting; 2006.
[44] Linden D. Handbook of batteries. 2nd ed.. New York, NY: McGraw-Hill; 1995.
[45] Sandia National Laboratory. 〈http://www.sandia.gov/ess〉.
[46] Renewable energy systems design assistant for storage. 〈http://www.ecn.nl/resdas〉.
[47] Electricity Storage Association. 〈http://electricty-storage.org〉.
[48] Hall PJ, Bain EJ. Energy-storage technologies and electricity generation. Energy Policy 2008;36:4352–5.
[49] 〈http://www.electricitystorage.org/tech/technologies_technologies.htm〉.
[50] 〈http://www.saftbatteries.com/〉.
[51] Leadbetter J, swan LG. Selection of battery technology to support grid integrated renewable electricity. J Power Sourc 2012;216:376–86.
[52] Zaghib K, Dontignya M, Guerfi A, Charest P, Rodrigues I, Mauger A, et al. Safe and fast-charging Li-ion battery with long shelf life for power applications. J Power Sourc 2011;196:3949–54.
[53] Wakihara M. Recent developments in lithium ion batteries. Mater Sci Eng 2001;33:109–34.
[54] Bradford R. Capturing grid power. IEEE Power Energy Mag 2009;7:32–41.
[55] Tan X, Li Q, Wang H. Advances and trends of energy storage technology in microgrid. Electr Power Energy Syst 2013;44:179–91.
[56] 〈http://www.ngk.co.jp/english/products/power/nas/index.html〉.
[57] Galloway RC, Dustmann C. ZEBRA battery-material cost availability and recycling. In: International electric vehicle symposium (EVS-20), Long Beach, Canada; 2003. p. 1–9.

[58] AEP Commissions First U.S. Demonstration of the NAS Battery, American Electric Power; 26 October 2007. 〈http://aeptechcentral.com/nasbattery.htm〉.
[59] Utility will use batteries to store wind power, The New York Times; 26 October 2007. 〈http://www.nytimes.com/2007/09/11/business/11battery.html?pagewanted=all〉.
[60] Baxter R. Energy storage—a nontechnical guide. Oklahoma: PennWell Corporation; 2006.
[61] Baker J. New technology and possible advances in energy storage. Energy Policy 2008;36:4368–73.
[62] Osaka T, Datta M. Energy storage systems in electronics. CRC Press, Boca Raton, Florida; 2000.
[63] Broussely M, Pistoia G. Industrial applications of batteries. From cars to aerospace and energy storage. Elsevier BV, Amsterdam, London; 2007.
[64] Lacerda VG, Mageste AB, Santos IJS, Silva LHMD, Silva MDVHD. Separation of Cd and Ni from Ni–Cd batteries by an environmentally safe methodology employing aqueous two-phase systems. J Power Sourc 2009;193:908–13.
[65] Nielsen KE, Molinas M. Superconducting magnetic energy storage (SMES) in power systems with renewable energy sources. In: IEEE international symposium on industrial electronics; 2010. p. 2487–92.
[66] Li G, Lu X, Coyle CA, Kim JY, Lemmon JP, Sprenkle VL, et al. Novel ternary molten salt electrolytes for intermediate-temperature sodium/nickel chloride batteries. J Power Sourc 2012;220:193–8.
[67] Brett DLJ, Aguiar P, Brandon NP. System modelling and integration of an intermediate temperature solid oxide fuel cell and ZEBRA battery for automotive applications. J Power Sourc 2006;163:514–22.
[68] Sudworth JL. Zebra batteries. J Power Sourc 1994;51:105–14.
[69] Chan CC. The state of the art of electric, hybrid, and fuel cell vehicles. Proc IEEE 2007;95:704–18.
[70] Hotza D, Costa JCDd. Fuel cells development and hydrogen production from renewable resources in Brazil. Int J Hydrog Energy 2008;33:4915–35.
[71] Song C. Fuel processing for low-temperature and high temperature fuel cells—challenges and opportunities for sustainable development in the 21st century. Catal Today 2002;77:17–49.
[72] Dicks AL, Costa JCDd, Simpson A, McLellan B. Fuel cells, hydrogen and energy supply in Australia. J Power Sourc 2004;131:1–12.
[73] European Commission. Hydrogen energy and fuel cells—a vision of our future. Luxembourg: Office for Official Publications of the European Communities; 2003.
[74] Steinfeld A, Meier A. Solar thermochemical process technology. Encycl Phys Sci Technol 2004;15:237–56.
[75] Martin E, Shaheen SA, Lipman TE, Lidicker JR. Behavioral response to hydrogen fuel cell vehicles and refueling: results of California drive clinics. Int J Hydrog Energy 2009;34:8670–80.
[76] 〈http://en.wikipedia.org/wiki/File:PEM_fuelcell.svg〉.
[77] Peihgambardoust SJ, Rowshanzamir S, Amjadi M. Review of the proton exchange membranes for fuel cell applications. Int J Hydrog Energy 2010;35:9349–84.
[78] Wang C, Mao Z, Bao F, Li X, Xie X. Development and performance of 5 kw proton exchange membrane fuel cell stationary power system. Int J Hydrog Energy 2005;30:1031–4.
[79] Lin M, Cheng Y, Yen S. Evaluation of PEMFC power systems for UPS base station applications. J Power Sourc 2005;140:346–9.
[80] Tuber K, Zobel M, Schmidt H, Hebling C. A polymer electrolyte membrane fuel cell system for powering portable computers. J Power Sourc 2003;122:1–8.
[81] Hwang JJ, Wang DY, Shih NC. Development of a lightweight fuel cell vehicle. J Power Sourc 2005;141:108–15.
[82] Hwang JJ, Wang DY, Shih NC, Lai DY, Chen CK. Development of fuel-cell-powered electric bicycle. J Power Sourc 2004;133:223–8.
[83] Folkesson A, Andersson C, Alvofors P, Alakula M, Overgaard L. Real life testing of a hybrid PEM Fuel cell bus. J Power Sourc 2003;118:349–57.
[84] Beckhaus P, Dokupil M, Heinzel A, Souzani S, Spitta C. On-board fuel cell power supply for sailing yachts. J Power Sourc 2005;145:639–43.
[85] Nguyen QM. Technological status of nickel oxide cathodes in molten carbonate fuel cells—a review. J Power Sourc 1988:1–19.
[86] Steele BCH. Material science and engineering: the enabling technology for the commercialisation of fuel cell systems. J Mater Sci 2001;36:1053–68.
[87] Dicks AL. Molten carbonate fuel cells. Curr Opin Solid State Mater Sci 2004;8:379–83.
[88] Andujar JM. Fuel cells: history and updating. A walk along two centuries. Renew Sustain Energy Rev 2009;13:2309–22.
[89] Bischoff M. Molten carbonate fuel cells: a high temperature fuel cell on the edge to commercialization. J Mater Sci 2006;160:842–5.
[90] Minh NQ. Solid oxide fuel cell technology—features and application. Solid States Ion 2004;174:271–7.
[91] Huang B, Qi Y, Murshed M. Solid oxide fuel cell: perspective of dynamic modeling and control. J Process Control 2011;21:1426–37.
[92] Sun C, Stimming U. Recent anode advances in solid oxide fuel cells. J Mater Sci 2007;171:247–60.
[93] Hajimolana SA, Hussaina MA, Daud WMAW, Soroush M, Shamiri A. Mathematical modeling of solid oxide fuel cells: a review. Renew Sustain Energy Rev 2011;15:1893–917.
[94] Hawkes AD, Aguiar P, Croxford B, Leach MA, Adjiman CS, Brandon NP. Solid oxide fuel cell micro combined heat and power system operating strategy: options for provision of residential space and water heating. J Mater Sci 2007;164:260–71.
[95] Colson C, Member S, Nehrir H. Evaluating the benefits of a hybrid solid oxide fuel cell combined heat and power plant for energy sustainability and emissions avoidance. IEEE Trans Energy Convers 2011;26:140–8.
[96] Koguchi H. Research, development, and deployment of fuel cells and hydrogen in Japan. In: IPHE Membership Meeting, Berlin; 2010.
[97] Aki H, Taniguchi Y, Tamura I, Kegasa A, Hayakawa H, Ishikawa Y, et al. Fuel cells and energy networks of electricity, heat, and hydrogen: a demonstration in hydrogen-fueled apartments. Int J Hydrog Energy 2012;37:1204–13.
[98] Kamarudin SK, Daud WRW, Ho SL, Hasran UA. Overview on the challenges and developments of micro-direct methanol fuel cells (DMFC). J Power Sourc 2007;163:743–54.
[99] Carrette L, Friedrich KA, Stimming U. Fuel cells—fundamentals and applications. Fuel Cells 2001;1:1–39.
[100] Verma LK. Studies on methanol fuel cell. J Power Sourc 2000;86:464–8.
[101] Baldauf M, Preidel W. Status of the development of a direct methanol fuel cell. J Power Sourc 1999;84:161–6.
[102] Kamarudin SK, Achmad F, Daud WRW. Overview on the application of direct methanol fuel cell (DMFC) for portable electronic devices. Int J Hydrog Energy 2009;34:6902–16.
[103] Han J, Liu H. Real time measurements of methanol crossover in a DMFC. J Power Sourc 2007;186:166–73.
[104] Wan CH. A composite anode with reactive methanol filter for direct methanol fuel cell. J Power Sourc 2009;186:229–37.
[105] Nakagawa N, Sekimoto K, Masdar MS, Noda R. Reaction analysis of a direct methanol fuel cell employing a porous carbon plate operated at high methanol concentrations. J Power Sourc 2009;186:45–51.
[106] Electricity Storage Association (ESA)—comparision of technology. 〈http://www.electricitystorage.org/technology/storage_technologies/technology_comparison〉.
[107] EIA. Emissions of greenhouse gases report; December 2008. Available from: 〈http://www.eia.doe.gov/oiaf/1605/ggrpt/carbon.html〉.
[108] Cetin E, Yilanci A, Oner Y, Colak M, Kasikci I, Ozturk HK. Electrical analysis of a hybrid photovoltaic-hydrogen/fuel cell energy system in Denizli, Turkey. Energy Build 2009;41:975–81.
[109] Hadjipaschalis I, Poullikkas A, Efthimiou V. Overview of current and future energy storage technologies for electric power applications. Renew Sustain Energy Rev 2009;13:1513–22.
[110] Boyes JD. Energy storage systems program report for FY99, SAND2000-1317; June 2000.
[111] Parker CD. Lead–acid battery energy-storage systems for electricity supply networks. J Power Sourc 2001;100:18–28.
[112] Zogg R, Lawrence T, Ofer D, Brodrick J. Distributed energy storage. ASHRAE J 2007;49:90–4.
[113] Oudalov A, Cherkaoui R, Beguin A. Sizing and optimal operation of battery energy storage system for peak shaving application. In: IEEE Power Tech, IEEE, Lausanne, Switzerland; 2007. p. 621–5.
[114] Skyllas-Kazacos M, Kasherman D, Hong DR, Kazacos M. Characteristics and performance of 1 kW UNSW vanadium redox battery. J Power Sourc 1991;35:399–404.
[115] Role of energy storage with renewable electricity generation. 〈http://www.nrel.gov/docs/fy10osti/47187.pdf〉 [accessed 31.08.12].
[116] Skyllas-Kazacos M, Chakrabarti MH, Hajimolana SA, Mjalli FS, Saleem M. Progress in flow battery research and development. J Electrochem Soc 2011;158:55–79.
[117] Eurelectric. Working group security of electricity supply. Security of electricity supply. Discussion paper; 2004.
[118] North American Electric Reliability Council (NERC). Glossary of terms. Prepared by the glossary of terms task force; 1996.
[119] Union for the Coordination of Transmission of Electricity (UCTE). UCTE operation handbook; 2004.
[120] Chakraborty A. Advancements in power electronics and drives in interface with growing renewable energy resources. Renew Sustain Energy Rev 2011;15:1816–27.
[121] U.S. Department of Energy: Smart grid. 〈http://energy.gov/oe/technologydevelopment/smart-grid〉 [accessed August 2012].
[122] Maitra A, Sundaram A, Gandhi M, Bird S, Doss S. Intelligent universal transformer design and applications. In: 20th international conference and exhibition on electricity distribution, IEEE, Prague, Czech Republic; 2009. p. 1–7.
[123] Li S, Feng X, Jia JB, Li K. A three-switch structure for PEMFC and ultra capacitor hybrid in backup power. In: IEEE sixth international on power electronics and motion control, IEEE, Wuhan, China; 2009. p. 2309–12.
[124] Dehaghi MA, Rajaei R, Ansari A. A new buck-and-boost ultra capacitor interface circuit for the HEVs. In: Fourth IEEE conference on industrial electronics and applications, IEEE, Melbourne, Australia; 2009. p. 3382–7.
[125] Miller JM, Yeung JCK, Ma YQ, Sartorelli G. Ultracapacitors improve SWECS low wind speed energy recovery. Ultracapacitor and battery for low wind energy harvesting. In: IEEE power electronics and machines in wind applications, IEEE, Lincoln, NE; 2009. p. 1–6.
[126] Wang L, Li H. Maximum fuel economy-oriented power management design for a fuel cell vehicle using battery and ultra capacitor. In: IEEE applied power electronics conference and exposition; 2009. p. 171–8.
[127] Han C, Huang AQ, Li D, Mamath H, Ingram M, Atcitty S. Modeling and design of a transmission ultra capacitor (TUCAP) integrating modular voltage source

converter with ultra capacitor energy storage. In: Annual IEEE on applied power electronics conference and exposition; 2006.
[128] Cheng DL, Wismer MG. Active control of power sharing in a battery/ultra capacitor hybrid source. In: Second IEEE conference on industrial electronics and applications; 2007. p. 2913–8.
[129] Marei MI, Samborsky SJ, Lambert SB, Salama MMA. On the characterization of ultra capacitor banks used for HEVs. In: IEEE vehicle power and propulsion conference; 2006. p. 1–6.
[130] Jia J, Wang G, Zhu Z, Cham YT, Han M. A clean power system combining fuel cell and ultra capacitor and its application in electric scooter. In: IEEE international conference on sustainable energy technologies; 2008. p. 389–93.
[131] Lee B-H, Shin D-H, Song H-S, Jeong J-B, Kim H-J, Kim B-W. The dynamic control of hybrid energy storage system for mild HEV. In: IEEE conference on vehicle power and propulsion; 2007. p. 796–801.
[132] Rajakaruna RMA. Small-signal transfer functions of the classical boost converter supplied by ultra capacitor banks. In: Second IEEE conference on industrial electronics and applications; 2007. p. 692–7.
[133] Drolia A, Jose P, Mohan N. An approach to connect ultra capacitor to fuel cell powered electric vehicle and emulating fuel cell electrical characteristics using switched mode converter. In: 29th annual conference of the IEEE on industrial electronics society; 2003. pp. 897–901.
[134] Lijun G, Dougal RA, Shengyi L. Power enhancement of an actively controlled battery/ultra capacitor hybrid. IEEE Trans Power Electron 2005;20:236–43.
[135] Lu S, Corzine KA, Ferdowsi M. A unique ultra capacitor direct integration scheme in multilevel motor drives for large vehicle propulsion. IEEE Trans Power Electron 2007;56:1506–15.
[136] Li., Liu D. Power distribution strategy of fuel cell vehicle system with hybrid energy storage elements using triple half bridge (THB) bidirectional DC–DC converter. In: Conference record of the 2007 IEEE industry applications conference; 2007. p. 636–42.
[137] Cegnar EJ, Hess HL, Johnson BK. A purely ultra capacitor energy storage system hybrid electric vehicles utilizing a based DC–DC boost converter. In: 19th annual IEEE on applied power electronics conference and exposition; 2004. p. 1160–4.
[138] Pagano M, Piegari L. Hybrid electrochemical power sources for onboard applications. IEEE Trans Energy Convers 2007;22:450–6.
[139] Stienecker AW, Stuart T, Ashtiani C. A combined ultra capacitor-lead acid battery storage system for mild hybrid electric vehicles. In: IEEE conference on vehicle power and propulsion; 2005.
[140] Bauman J, Kazerani M. An analytical optimization method for improved fuel cell–battery ultra capacitor power train. IEEE Trans Veh Technol 2009;58: 186–97.
[141] Haihua Z, Khambadkone AM. Hybrid modulation for dual-active-bridge bidirectional converter with extended power range for ultra capacitor application. IEEE Trans Ind Appl 2009;45:1434–42.
[142] Uzunoglu M, Alam MS. Dynamic modeling, design, and simulation of a combined PEM fuel cell and ultra capacitor system for stand-alone residential applications. IEEE Trans Energy Convers 2006;21:767–75.
[143] Dixon JW, Ortuzar ME. Ultra capacitors + DC–DC converters in regenerative braking system. IEEE Aerosp Electron Syst Mag 2002;17:6–21.
[144] Netra G, Yasuharu O. Effective voltage and frequency control strategy for a stand-alone system with induction generator/fuel cell/ultra capacitor. In: Integration of wide-scale renewable resources into the power delivery system, CIGRE/IEEE PES joint symposium; 2009. p. 1–11.
[145] Miller JM, Deshpande U, Dougherty TJ, Bohn T. Power electronic enabled active hybrid energy storage system and its economic viability. In: 42nd IEEE APEC; 2009. p. 1–5.
[146] Yu H, Cui S, Wang T. Simulation and performance analysis on an energy storage system for hybrid electric vehicle using ultra capacitor. In: IEEE vehicle power and propulsion conference; 2008. p. 1–5.
[147] Lu Y, Hess HL, Edward DB. Adaptive control of an ultra capacitor energy storage system for hybrid electric vehicles. In: IEEE international conference on electric machines and drives; 2007. p. 1–6.
[148] Miller JM, Everett M, Auer J. Ultra capacitor enabled gatekeeper energy management strategy for single mode eCVT hybrid vehicle propulsion. In: IEEE vehicle power and propulsion conference; 2006. p. 1–6.
[149] Lukic SM, Wirasingha SG, Rodriguez F, Cao J, Emadi A. Power management of an ultra capacitor/battery hybrid energy storage system in an HEV. In: IEEE vehicle power and propulsion conference; 2006. p. 1–6.
[150] Glavin ME, Hurley WG. Ultra capacitor/battery hybrid for solar energy storage. In: 42nd international universities power engineering conference; 2007. p. 791–5.
[151] Auer J, Sartorelli G, Miller J. A gatekeeper energy management strategy for ECVT hybrid vehicle propulsion utilizing ultra capacitors. In: IET hybrid vehicle conference; 2006. p. 79–90.
[152] Ubong EU, Mizell C, Slota G, Lovria N. Ultra capacitor with Ballard Nexa in a GEM vehicle in a hybrid mode. In: Electrical insulation conference and electrical manufacturing expo; 2005. p. 317–20.
[153] Haihua Z, Khambadkone AM. Hybrid modulation for dual active bridge bi-directional converter with extended power range for ultra capacitor application. In: IEEE industry applications society annual meeting; 2008. p. 1–8.
[154] Jayawickrama YRL, Rajakaruna S. Ultra capacitor based ride-through system for a DC load. In: International conference on power system technology; 2004. p. 232–7.
[155] Cheung KYC, Cheung STH, Silva N, et al. Large-scale energy storage systems. Imperial College London, ISE2; 2002/2003. Available from: 〈http://www.homes.doc.ic.ac.uk/~matti/ise2grp/energystorage_ report/〉 [accessed 20. 03.07].
[156] 〈http://www.beaconpower.com/products/EnergyStorageSystems/DocsPresentations.htm〉.
[157] Lazarewicz M, Arseneaux J. Flywheel-based frequency regulation demonstration projects status. In: EESAT conference, San Francisco, USA; 2005. p. 1–22.
[158] Walawalkar R, Apt J. Market analysis of emerging electric energy storage systems. Carnegie Mellon Electricity Industry Center, National Energy Technology Laboratory, Pittsburgh, Pennsylvania; 2008.